Creep and Shrinkage Losses in Prestressed Concrete Bridges in Highly Variable Climates

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ABSTRACT

Past field measurement of prestress losses in areas with highly variable daily relative humidity (RH) and temperature have indicated that excessive time-dependent losses beyond AASHTO prediction could occur. Studies have also suggested that moist-curing after prestressing of post-tensioned members can reduce long-term losses. To systematically measure the effects of climatic exposure, moist curing, and aggregate type, prestress variations were studied in twelve post-tensioned beams built in Northern and Southern Nevada. The focus of the part of the study presented in this article is on the beams in Northern Nevada. A large number of concrete cylinders were also used to measure creep and shrinkage deformations and to study the effect of moisture on the modulus of elasticity. Several of the beams showed losses that exceeded the AASHTO prediction. The extrapolated measured data were used as the basis to propose modifications to the AASHTO equations to estimate creep and shrinkage losses.

INTRODUCTION

The effects of highly variable climate, moisture, as well as aggregates can be important on creep and shrinkage losses in prestressed concrete structures. Several previous studies have monitored the losses in full-scale box-girder bridges. These studies have found that current methods, particularly the method set forth by the American Association of State Highway and Transportation Officials (AASHTO) (*1*), of predicting losses due to creep and shrinkage can underestimate the losses that are commonly experienced in prestressed box girders located in regions with a highly varying climate.

From a previous study performed in Northern Nevada by Mangoba et al. (*2*), it was noted that the relative humidity (RH) can range from 14% to 100%, and within the same 24-hour period RH can vary from 15% to above 80%. On any given day, relative humidity can vary drastically, which can have an effect on the amount of creep and shrinkage losses seen in prestressed concrete. This could be a concern since most of the current design guidelines for predicting prestress losses are based on studies performed under nearly constant RH. The potential detrimental effects of highly variable RH on prestress losses has prompted several studies to determine the actual losses that can be expected under this types of climate. Mangoba's study also suggested that a period of moist weather following the application of prestress can reduce creep and shrinkage losses, while a drier period following the application of prestress can have the opposite effect in post-tensioned structures.

Aggregate type also can heavily affect the magnitude of creep and shrinkage losses in prestressed concrete over the lifetime of a structure. Some of the characteristics of aggregate that have a major influence on the susceptibility to creep and shrinkage include modulus of elasticity, aggregate content in concrete, absorption, cleanliness, and thermal expansion coefficient. In articles by Mehta and Monteiro (*3*) and Alexander (*4*) comprehensive evaluation of creep and shrinkage properties of different aggregates were presented, demonstrating the relationship of creep and shrinkage susceptibility to aggregate type. Alexander suggested that andesite, the aggregate used in Northern Nevada and chosen for this study, while in comparison to other aggregates has average shrinkage susceptibility, can experience 20% more creep than average. Mehta and Monteiro suggested that of all the aggregate characteristics contributing to creep and shrinkage, modulus of elasticity is the most influential.

Previous field studies performed in Reno and Las Vegas were focused on measuring prestress losses in full-scale post-tensioned box girder bridges. Saiidi and Shields studied the Golden Valley Bridge in Reno (*5 and 6*), Saiidi et al. studied the Greenway Bridge in Las Vegas (*7 and 8*), and Mangoba et al. studied four bridges in the Reno area stressed on different dates at the South Meadows Interchange, the Mount Rose Interchange, the Zolezzi Lane Grade Separation, and the Old Virginia Road Grade Separation (*2*). Saiidi and Shields found that in Reno, AASHTO underestimated the losses in the Golden Valley Bridge due to creep and shrinkage by 60%. Saiidi et al. found for the Greenway Bridge in Las Vegas that AASHTO was conservative by 30% in the estimation of creep and shrinkage losses. Mangoba et al. found that AASHTO overestimated creep and shrinkage losses in the Zolezzi and the Mount Rose bridges by 31% and 7%, respectively. They also found that the losses in the South Meadows and Old Virginia bridges were underestimated by AASHTO by 7% and 30%, respectively. It was noted that the Zolezzi Lane and Old Virginia bridges were exposed to unusual conditions following stressing. For the first week following stressing, the bridge at Old Virginia Road was subject to a drop in RH, which is believed to be responsible for the excessive loss. In contrast, the Zolezzi Lane Bridge was subjected to relatively high moisture and experienced low losses.

OBJECTIVES

The study discussed in this paper, represents a portion of a study (*9*) with several objectives. The objectives discussed in this paper consisted of quantifying the effects of moist curing prestressed concrete for a period of time following the application of prestress, studying the effects of this type of curing on box girders and solid beams, and to propose revisions to the current AASHTO equations for creep and shrinkage loss prediction.

EFFECTS OF MOISTURE

In the study performed by Mangoba et al. on prestressed box girder bridges, the effects of moisture on prestressed concrete following the application of prestress were seen to have a beneficial effect on the creep and shrinkage losses in one of the bridges studied. Water was inadvertently spilled on the Zolezzi Lane Bridge, and since the drains were not yet functional, the bridge was subjected to standing water for several days shortly after the application of prestress. As a result the Zolezzi Lane Bridge experienced lower losses than other three bridges monitored in the study.

In an attempt to quantify the effects of moisture on newly prestressed concrete, the properties of concrete were studied to find possible characteristics that would interact with the moisture to produce lower creep and shrinkage losses. The modulus of elasticity was found to be a property heavily influenced by moisture. Neville (*10*) suggested an increase in stiffness of 24% for wet concrete versus dry, while Mehta and Monteiro reported a 15% increase in concrete stiffness due to moisture. Further research revealed that the elastic modulus of cement paste varied greatly with RH. Ramachandran (*11*) suggested that the modulus of elasticity of cement paste remains constant as relative humidity increases to 50%. Then it increases to more than 150% of the original value at 100% relative humidity (Fig. 1).

To help determine what the effects of moisture would be on the concrete used in this study, elastic modulus was measured on five eleven-month old cylinders from the box girder specimens (described in the following sections). The cylinders were subjected to several wet-dry cycles. The cylinders were dried in an oven at 100°C (212°F) until they achieved a constant weight at which point they were assumed to be dry. The elastic modulus of the cylinders was then measured. Immediately following the tests, the cylinders were placed in a moist room for approximately one week, where they were subjected to a RH of 100% and some direct moisture from the emitters. Following exposure in the moist room, the elastic modulus was measured again and the cylinders were put back into the oven.

The average elastic modulus value measured from the cylinders after the initial drying period was 31400 MPa (4550 ksi). Following the first period of moisture, the average elastic modulus value had increased to 36200 MPa (5250 ksi). The second drying period lowered the average measured elastic modulus value to 29400 MPa (4270 ksi), which increased to 38200 MPa (5540 ksi) following the second moist period. The data showed an average increase of 19% in the elastic modulus of the concrete as RH was changed from zero to 100%. The measured increase was in the range of data reported by Neville (*10*) and Mehta and Monteiro (*3*).

To help quantify the effects of moisture on concrete, data from a chart in Ref. 11 were used. Since it was shown that cement paste was unaffected by changes in relative humidity up to 50%, concrete was assumed to behave in a similar fashion. However, since the elastic modulus of cement paste increases by 50% at 100% RH whereas the increase for the concrete cylinders was only approximately 20%, the behavior of the cement paste above 50% relative humidity was scaled to reflect the increase of only 20% for concrete (Fig. 1). An equation of the scaled curve was developed to allow for the adjustment of the elastic modulus as a function of RH and was used in analytical studies. This equation produces a modification factor for the elastic modulus of concrete exposed to relative humidity above 50%.

$$X_E = 0.000093RH^2 - 0.0101RH + 1.2766 \quad (1)$$

Time step analysis methods have been developed to estimate prestress losses as a function of time. Naaman's method (*12*) was used in conjunction with Eq. 1 to modify the elastic modulus and study the effects of variation of relative humidity on long-term creep and shrinkage losses. Figure 2 demonstrates the effects of one week and two week periods of exposure to RH that is different than an ambient RH of 50% on a beam similar the box girder specimens described later. Steel relaxation losses are not included. From this figure, it is shown that moist curing at RH of 100% for two weeks following the application of prestress can reduce the creep and shrinkage losses by 18%, and a very dry period (0% RH) in the first two weeks after stressing can increase losses by 12%.

PRESTRESS LOSS STUDIES

The second objective of this study was to construct and monitor post-tensioned concrete members to determine the effects of moist curing for a period of time following the application of prestress. Since previous work was done on bridges in the field, it was desired to conduct a study in a more controlled setting with more test groups. The purpose of the study was to measure creep and shrinkage losses for a period of time following prestressing and extrapolate the data to estimate long-term losses. From this information, recommendations for design and construction of prestressed concrete beams may be suggested.

Two types of concrete beams were included in the study. The first was a single-cell box girder and the second type was a solid beam. All the beams were concentrically prestressed. In addition to concrete cylinders taken from each batch of concrete to measure the compressive strength, several sets of cylinders were taken to measure deformations due to creep and shrinkage as a function of time.

Design

Box Girders

Four box girders were designed and constructed to model a single cell of a typical box girder bridge. The box girders were approximately one-quarter scale models and were designed based on AASHTO guidelines for prestressed concrete taking into account ease of construction and monitoring. The specified 28-day concrete compressive strength was 41.4 MPa (6 ksi).

Figure 3 shows the details of the box beams. In the bottom center section of each box girder an opening was left for access to the cell. The ends of each beam were left solid with end plates to distribute the loading. Each girder was reinforced with four 15 mm (0.6 in.) diameter seven-wire Grade 270 strands as shown in the figure. In addition nominal Grade 60 mild steel was placed in the longitudinal and transverse directions to provide strength prior to prestressing. The design prestress force was determined to produce a maximum compressive force of 55% f'_{ci} (the estimated concrete strength at time of stressing) in the mid-section of the girders. This led to an initial tendon stress of 65% of the specified ultimate strength (f_{pu}).

Solid Beams

Figure 3 shows details of the solid beams, two of which were built. Each beam was prestressed with a central 15 mm (0.6 in.) diameter seven-wire strand. In addition nominal Grade 60 mild steel was used in the section to provide strength during handling of the beams prior to stressing. The tendon maximum stress at time of stressing was set at 70% of the specified ultimate strength. This led to a maximum concrete stress of 45% of the specified 28-day concrete compressive strength. Each solid beam was placed over two end supports and a support at the center to reduce moment under self-weight. The ends of each beam were capped with a steel plate to distribute the prestress force.

Material Properties

Prestressing Steel

The prestressing steel used in the beam specimens was 15 mm (0.6 in.) diameter, stress-relieved, seven-wire, grade 270 strands (ASTM A416). The material properties of the prestressing steel were measured at the NDOT Materials Division. The measured elastic modulus of the tendons was 193,800 MPa (28,100 ksi) and the measured ultimate strength was 1,930 MPa (280 ksi).

Concrete

The beams were constructed with normal weight concrete. The mineral content of the aggregate used in the concrete was mainly andesite. The concrete in the box girders had a twenty-eight day compressive strength of 46.2 MPa (6.7 ksi). The concrete in the solid beams had a twenty-eight day strength of 28.3 MPa (4.1 ksi).

Variables and Naming Convention

For the purposes of this study, two main variables were used. The first variable was the curing condition following tensioning. Two curing processes were used, the first was air curing or no treatment and the second was moist curing. To moist cure the beams, they were covered with cloth or batting, and moistened twice a day for the first two weeks. The second variable was the environment to which each specimen was exposed. The first climate was indoors, where the beams were subjected to a controlled laboratory environment with nearly constant temperature and RH. The second environment was outdoors, where the beams were subjected to precipitation (rain and snow) and a relatively large range of temperatures and RH. The effect of climate was studied only in box girders.

In order to distinguish between test specimens, a naming convention was developed. The first two letters of each specimen's name corresponded to the specimen location, Reno (RN). The third letter of each specimen's name corresponded to the exposure climate, indoor (I) and outdoor (O). The fourth letter of each specimen's name corresponds to the curing of the specimen, moist (M) and air (A). Finally, the last letter of each specimen's name corresponds to the type of specimen, solid beam (S) and box girder (B).

Instrumentation

The beams were instrumented with two types of strain gages. The prestressing tendons had electric resistance strain gages mounted directly on the individual wires, and mechanical gages were mounted to the surface of the concrete.

The box girders were instrumented with 12 electric resistance strain gages, three per tendon, on alternating exterior strands. Each box girder was instrumented with two mechanical gages, each with a 457 mm (18 in.) gage length. The mechanical gages were mounted at mid-depth of each web, centered on the beam span. The location of the mechanical gages was not critical since the stress distribution in the cross-section of each beam was uniform.

The solid beams were instrumented with 8 electric resistance strain gages, mounted on each exterior wire with two redundant gages. Two mechanical gages were mounted on each solid beam with a 1.067 m (42 in.) gage length. The gages were mounted end to end down the center of the top of the beams.

Prestressing

The tendons in the box girders were stressed one at a time following a diagonal sequence. The prestress force was monitored during prestressing using the electrical strain gages. Prestressing force was applied in two steps. Approximately 70% of the target prestress was applied during the first step on all four tendons, and the remainder was applied in the second step. To compensate for immediate losses due to elastic shortening and anchorage set, the force at time of release was allowed to exceed the target by approximately ten percent. The box girders were stressed on January 12, 2000.

Stressing of the solid beams was straightforward. The tendons in the solid beams were also overstressed to compensate for the immediate losses. The solid beams were stressed on May 23, 2001.

Data Collection Schedule

With the exception of the first few weeks following the application of prestress, when daily measurements were taken, data were taken monthly in the beams and the creep and shrinkage cylinders. The data were collected typically in the morning.

Measured Tendon Stresses

Time dependent losses in prestressed concrete members consist of losses due to concrete shrinkage, concrete creep, and tendon relaxation. While the first two are associated with deformation and strains, the relaxation of tendon is the loss of force under constant strain and it is not hence associated with strain. As a result the strain data that were collected only indicate the combined prestress losses due to creep and shrinkage. Temperature and relative humidity values were also measured when data were collected and the gage readings were corrected for temperature effects. The corrections were made using the coefficients of thermal expansion for the materials used with each gage and the difference in temperature from the time of initial stressing to the time of data collection.

The measured data were plotted and studied over time. The data collected from the box girders span two and a half years. Figure 4 shows the measured tendon stresses as a function of time. To obtain the stresses the average measured strains from the electric and mechanical gages were multiplied by the measured modulus of elasticity of the tendons. As expected, tendon stresses generally drop as a function of time. The curves for the indoor beams are smooth because changes in temperature and humidity were relatively minor indoors. The results for the outdoor beams, however, show an oscillation of stresses. The upward slope in these curves occurs in winter months and is attributed to absorption of ambient moisture, which in turn causes expansion of the concrete and additional stressing of the tendons. An opposite effect is observed during summer months when the dry ambient air leads to high shrinkage of the beams and relatively large losses. The stress losses during the first two months in the indoor beams exceeded those of the outdoor beams. This is because of intermittent rain and snow following the stressing, which affected the outdoor beams and not the indoor beams.

The data collected from the solid beams cover a period of over one year. The electric gage data from the solid beams were not considered, as they were deemed unreliable by comparisons with the mechanical gage data and the climatic data. The sensitivity of tendon stresses to variation in the climatic conditions is similar to the box girders in Fig. 4, and can be seen in Fig. 6. Intermittent rain during the third week after stressing helped recover at least a part of the prestress force.

The beams all had slightly different initial stress values after the tendons were released and set. To facilitate comparison among different beams, the percentage of prestress losses as a function of the initial prestress was plotted for each beam group (Figs. 5 and 6). The smooth variation of prestress force for the indoor box girders and the contrast with the oscillation of tendon stresses in the outdoor girders with climatic changes is clearly seen in Fig. 5. The effect of initial moist curing was minimal for the indoor girders for the first two years. The outdoor girder that was moist cured (RNOMB), however, exhibited lower losses than RNOAB throughout the data collection period. The moist-cured solid beam also consistently showed lower losses than the air-cured solid beam (Fig. 6).

In addition to prestress variations, creep and shrinkage losses were measured but are not presented herein due to limited space. The data are discussed in Ref. 9, but are used in subsequent sections of this article.

Comparison of Measured and Calculated Losses

Bridge performance is an issue over the lifetime of a structure, and creep and shrinkage produce losses throughout the lifetime of a structure. However, most of these losses occur in the first year of the structures lifetime. Therefore, in order to compare long-term losses with the data taken in a relatively short period of time, the measured losses were extrapolated to 40 years and were listed in Table 1. The estimated long-term losses were compared with creep and shrinkage losses determined using the AASHTO provisions and those from the Naaman (*12*) and Nawy (*13*) time-step analysis methods. By comparing the results with the AASHTO estimates it was possible to determine the applicability of the AASHTO creep and shrinkage equations to the test beams. This was important because AASHTO provisions are routinely used to calculated prestress losses. Comparison with the more elaborate and detailed time-step analysis methods allowed these models to be evaluated in light of extrapolated measured data.

The extrapolated data show that creep and shrinkage losses in the moist cured beams were 15% lower than that of air-cured beams (Table 1). The box beams showed larger losses than the solid beams in part because of the lower volume to surface (V/S) ratio for the box section. The V/S for the box sections was 0.75 and for the solid beams was 1.25.

Table 1 lists the prestress loss values estimated from the AASHTO method as well as a summary of the extrapolated beam data. The Reno outdoor moist cured box girder (RNOMB) showed an extrapolated loss of 238 MPa (34.6 ksi), which is 3% lower than the 246 MPa (35.6 ksi) predicted by AASHTO. The loss in the Reno outdoor air cured box girder (RNOAB) was 15.7% higher than the AASHTO estimate of 241 MPa (35.0 ksi), with an extrapolated loss of 280 MPa (40.6 ksi). The AASHTO method underestimated the loss in the Reno indoor moist cured box girder (RNIMB), which had a loss of 323 MPa (46.8 ksi), by 21.5% with a predicted loss of 265 MPa (38.4 ksi). The 260 MPa (37.7 ksi) loss experienced by the Reno indoor air cured box girder was 8.9% higher than the AASHTO prediction of 239 MPa (34.6 ksi).

The Reno outdoor moist cured solid beam (RNOMS) showed an extrapolated loss of 163 MPa (23.6 ksi), which is 29.0% lower than the estimate of 232 MPa (33.6 ksi) calculated from the AASHTO method. The estimate using the AASHTO method was also conservative by 68.0% with a loss of 207 MPa (30.1 ksi) when compared to the Reno outdoor air cured solid beam (RNOAS) extrapolated loss of 83 MPa (12.0 ksi).

With respect to percent losses, the two outdoor box girders (RNOMB and RNOAB) averaged an extrapolated loss of 22.0% compared to the indoor box girders (RNIMB and RNIAB) that had an average extrapolated loss of 23.7%. The difference in these values can be attributed to the different climatic exposures. RNIMB has a larger extrapolated loss than RNIAB, 25.9% versus 21.8%, when the electric gage data is considered, however when looking at the mechanical gage data, these two beams experienced similar losses at 23.5%. The average of the two types of gages has RNIMB seeing larger losses at 24.7% than RNIAB at 22.7%. When considering the outdoor box girders RNOMB at 20.0% for both electric resistance and mechanical gages has a lower extrapolated loss than RNOAB, which had an electric gage loss of 21.8% and a mechanical gage loss of 26.2%. The electric gages show RNOMS experiencing higher losses at 9.5% versus RNOAS at 5.6%.

The time-step methods proposed by Nawy (*12*) and Naaman (*13*) were also used for comparison of the results with the measured data. The time-steps were taken to coincide with the days data were taken, and for forty year projections, the data was taken at monthly intervals up to 1000 days and then yearly to 40 years. The average ambient relative humidity for Reno was taken to be 50%. Table 1 shows the estimates and comparisons for these methods. The relaxation losses are taken into account for creep calculations but are excluded from the results.

The time-step method proposed by Naaman underestimated the losses in RNOMB by 43%, RNOAB by 71%, RNIMB by 79%, and RNIAB by 61%. The estimate was conservative for the solid beams, 34% for RNOMS and 62% for RNOAS.

The time-step method proposed by Nawy also underestimated the losses in the box girders. Nawy's method underestimated RNOMB by 14%, RNOAB by 36%, RNIMB by 42% and RNIAB by 28%. The estimate for RNOMS was conservative by 37%, and the estimate for RNOAS was also conservative by 64%.

REVISIONS TO AASHTO

The third objective of this study was to analyze the measured data and propose any necessary revisions to the current AASHTO method. The data discussed in the previous section showed that the AASHTO provisions for creep and shrinkage losses can be unconservative and that a revision of the equations is necessary. Before developing a modification to the current AASHTO equations, the origin of the equations was searched. The AASHTO equations are reported to have been based on the work by Shorer (*14*). Therefore, Shorer equations in conjunction with the current AASHTO equations and data extrapolated from the concrete cylinders were studied to help develop possible revisions.

The AASHTO equation for long-term shrinkage loss in pretensioned members is:

$$SH = 117 - 1.03 * RH \text{ (MPa)}$$

$$SH = 17000 - 150 * RH \text{ (psi)} \qquad (2)$$

In which RH = relative humidity (%)

The relationship for Eq. 2 is shown in Fig. 7. For post-tensioned concrete, the equation is multiplied by a factor of 0.8. This basic form was preserved in the development of the new equation. Shorer's equation produces a line nearly twice what AASTHO equation predicts (Fig. 7).

$$SH = 225 - 2.25 * RH \text{ (MPa)}$$

$$SH = 32625 - 326.5 * RH \text{ (psi)} \qquad (3)$$

The extrapolated data from the shrinkage cylinders was averaged to develop an ultimate shrinkage value for the concrete used, and to produce an equation of format similar to that of AASHTO and Shorer. Since the data from the cylinders did not cover a sufficiently wide range of RH, they were not seen as being adequate to develop an equation solely on the average of these points. Therefore, based on average of the values suggested by ACI Committee 209 (*15*) and PCI (*16*), an ultimate shrinkage value of 800 microstrain was assumed to be the value at 0% humidity. To develop an equation, another data point was needed; therefore the ultimate shrinkage at 100% relative humidity was taken to be zero. Using these two data points a new equation was developed.

$$SH = 159 - 1.59 * RH \text{ (MPa)}$$

$$SH = 23000 - 230 * RH \text{ (psi)} \qquad (4)$$

This equation was taken to be for pretensioned concrete, and by multiplying this equation by 0.8 the equation for post-tensioned concrete was produced. Figure 7 shows a comparison of the shrinkage equations.

The equation the AASHTO method suggests for predicting creep losses is:

$$CR = 12\, f_{cir} - 7\, \Delta f_{cds} \qquad (5)$$

In which f_{cir} = concrete stress at center of gravity of prestressing steel at transfer

Δf_{cds} = change in prestress in concrete stress at center of gravity of prestressing steel due to superimposed permanent loads.

Shorer's equation for creep loss estimate depends not only on the stresses present in the concrete, but the ambient RH.

$$CR = 41.47 * \frac{(125 - RH)}{100} * f_{cir} \qquad (6)$$

Similar to what was done for shrinkage, the extrapolated creep data were used along with the 13.8 MPa (2000 psi) that the creep cylinders were stressed to develop a new equation. Since the beams used in this study had no superimposed loading after prestressing, only the first term in Eq. 5 was manipulated. The resulting equation was:

$$CR = 17\, f_{cir} - 7\, \Delta f_{cds} \qquad (7)$$

Equation 7 would increase the estimate of creep loss by 40% compared to the AASHTO method. It was felt that the limited number of measured data points in this study could not justify such a large increase, and hence, a value of 15 was chosen for the coefficient of the first term leading to the following final proposed equation:

$$CR = 15\, f_{cir} - 7\, \Delta f_{cds} \qquad (8)$$

Table 1 shows the total creep and shrinkage loss predictions based on the proposed equations. The existing AASHTO equations underestimated the losses in RNOAB, RNIAB, and RNOMS, with the maximum difference being 22%. With the proposed equations the estimates of creep and shrinkage losses are conservative for all the beams.

CONCLUSIONS

The data collected from the elastic modulus tests suggests that the reason that moisture helps reduce losses is the change in stiffness. The modulus of elasticity in concrete cylinders kept in a moist room was found to be approximately 20% higher than that of dry concrete cylinders.

From the extrapolated measured prestress losses, it was found that the box girders were more susceptible to the effects of moisture than the solid beams due to the higher surface to volume ratios. The trends in the measured data also suggest that a period of moist curing following stressing along with continued moisture in the form of precipitation helps reduce long-term losses, but the effects of the moist curing are less noticeable if there is no further moisture beyond the initial moist curing.

The AASHTO method underestimated creep and shrinkage losses in three of the box girders by 9 to 22%. New proposed equations were developed for areas with highly variable climate. The format of the equations was kept the same as that of AASHTO equations. The creep and shrinkage losses estimated using the proposed equations were found to be conservative for all the six test beams.

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LIST OF TABLES AND FIGURES

FIGURE 6 Solid Beam Mechanical Gage Loss as a Percentage of Initial Prestress
FIGURE 7 Shrinkage Equation Comparisons

TABLE 1 Comparison of Measured Results and Estimates

	RNOMB	RNOAB	RNIMB	RNIAB	RNOMS	RNOAS
Initial Stress (MPa*)	1193	1166	1311	1148	1713	1478
Measured Extrapolated Loss (MPa*)						
Electric Gages	238	255	339	251	-	-
Mechanical Gages	239	305	307	270	163	83
Average	238	280	323	260	163	83
Measured Extrapolated Loss (%)						
Electric Gages	20.0	21.8	25.9	21.8	-	-
Mechanical Gages	20.0	26.2	23.5	23.5	9.5	5.6
Average	20.0	24.0	24.7	22.7	9.5	5.6
AASHTO (MPa*)	246	241	265	238	232	207
Modified AASHTO (MPa*)	305	300	329	296	288	257
Measured / AASHTO	0.97	1.16	1.22	1.09	0.71	0.40
Measured / Modified AASHTO	0.78	0.93	0.98	0.88	0.57	0.32
Naaman Time-Step (MPa*)	167	164	180	162	247	220
Nawy Time-Step (MPa*)	210	206	227	203	258	230
Measured / Naaman	1.43	1.71	1.79	1.61	0.66	0.38
Measured / Nawy	1.14	1.36	1.42	1.28	0.63	0.36

*1 MPa = 0.145 ksi

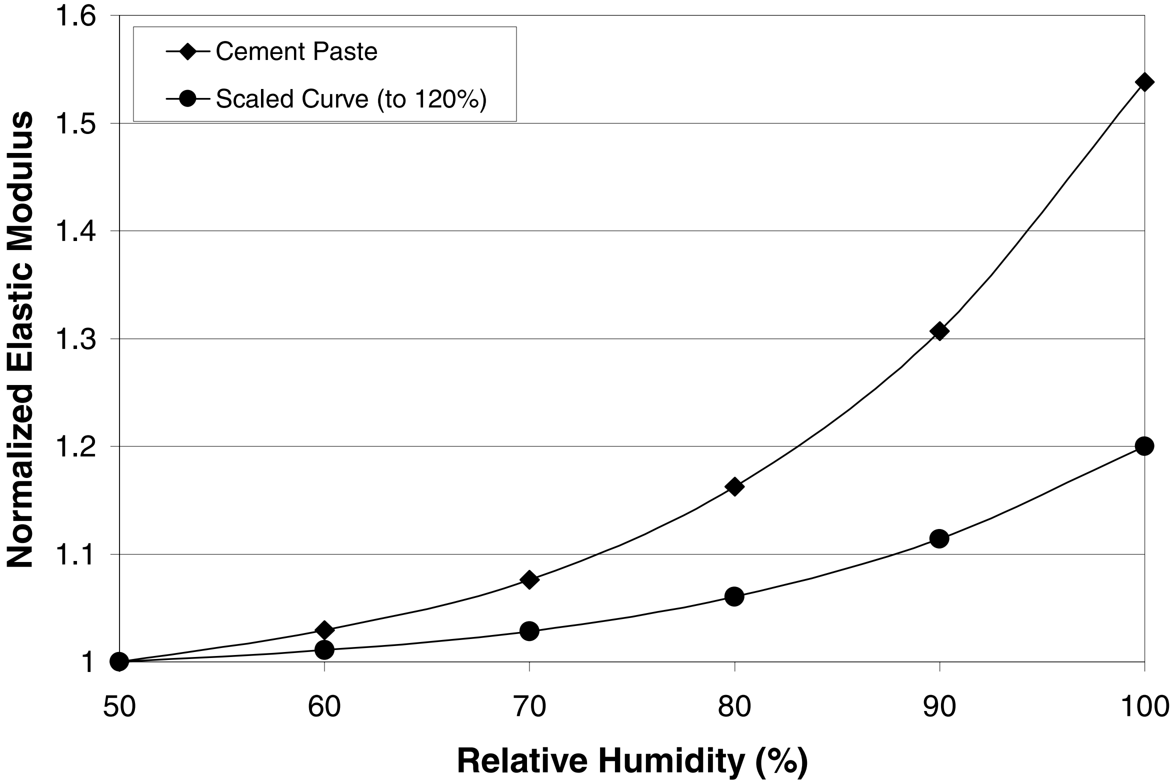

FIGURE 1 Effect of RH on Elastic Modulus of Cement Paste (After Ref. 11)

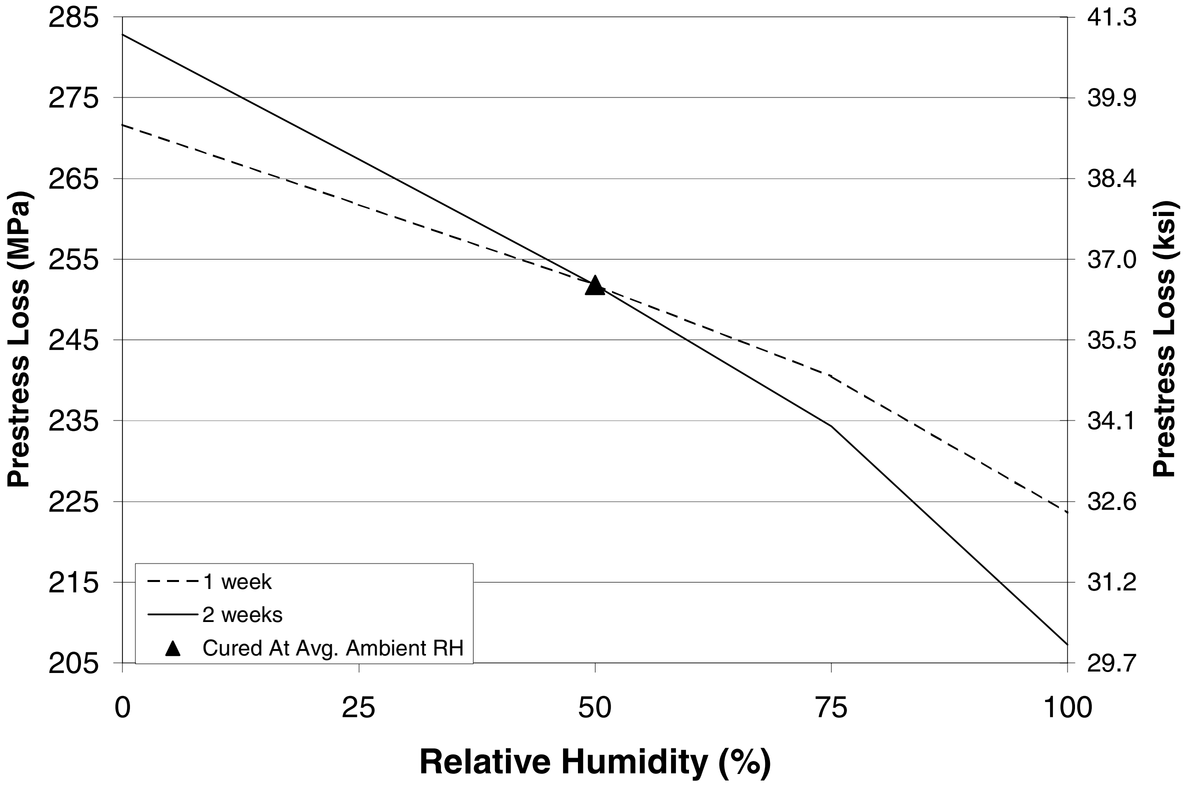

FIGURE 2 Prestress Loss Comparison With Curing and Modified Elastic Modulus Using Naaman's Time-step Method (*10*)

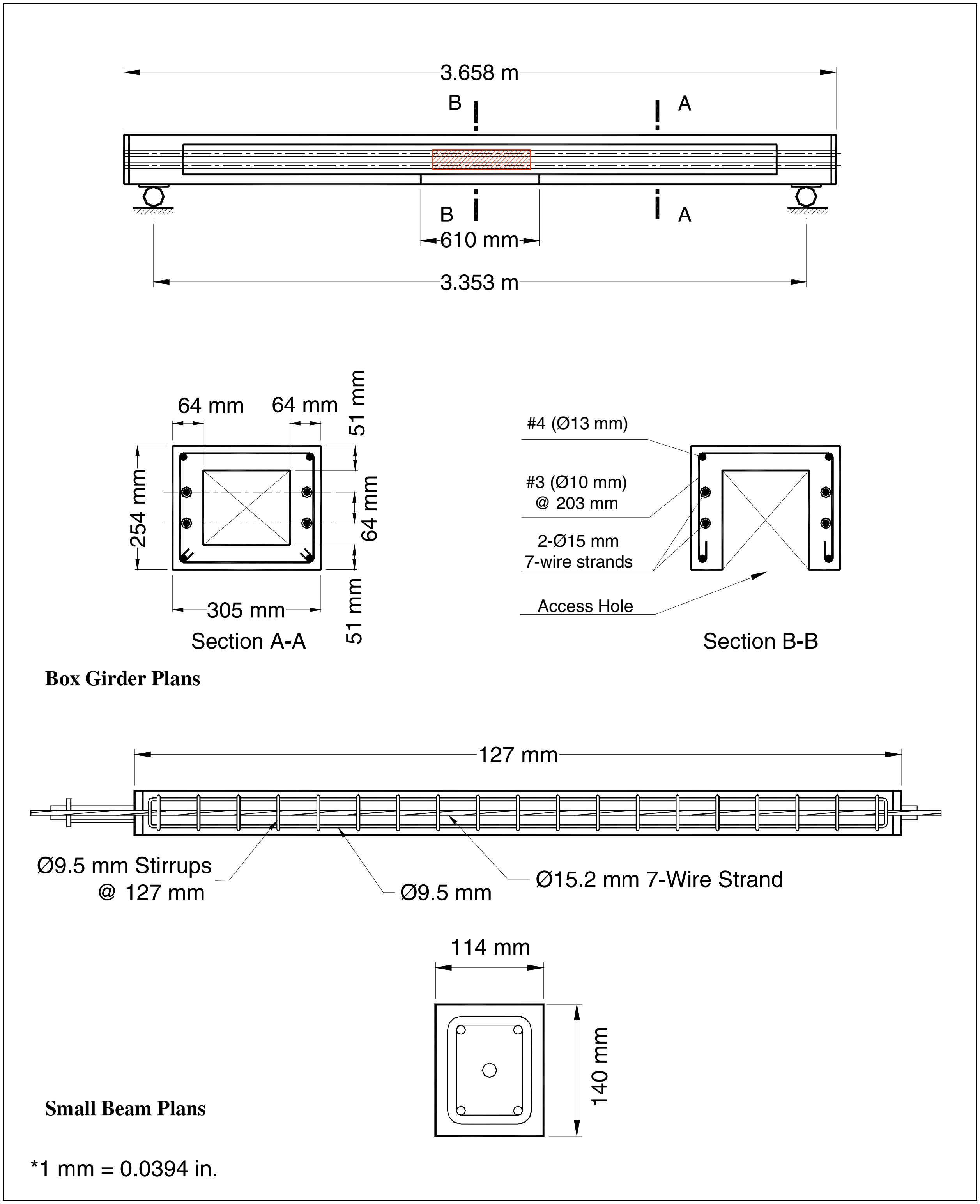

FIGURE 3 Beam Specimen Plans

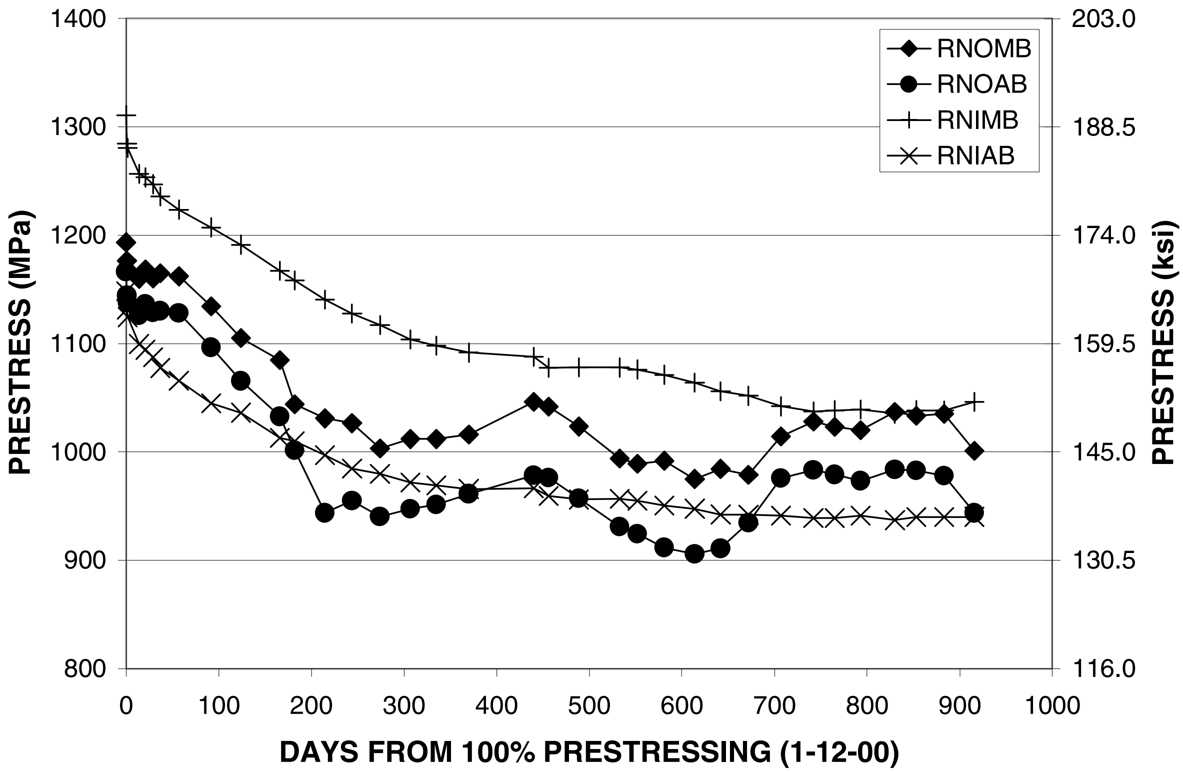

FIGURE 4 Box Girder Average Measured Prestress

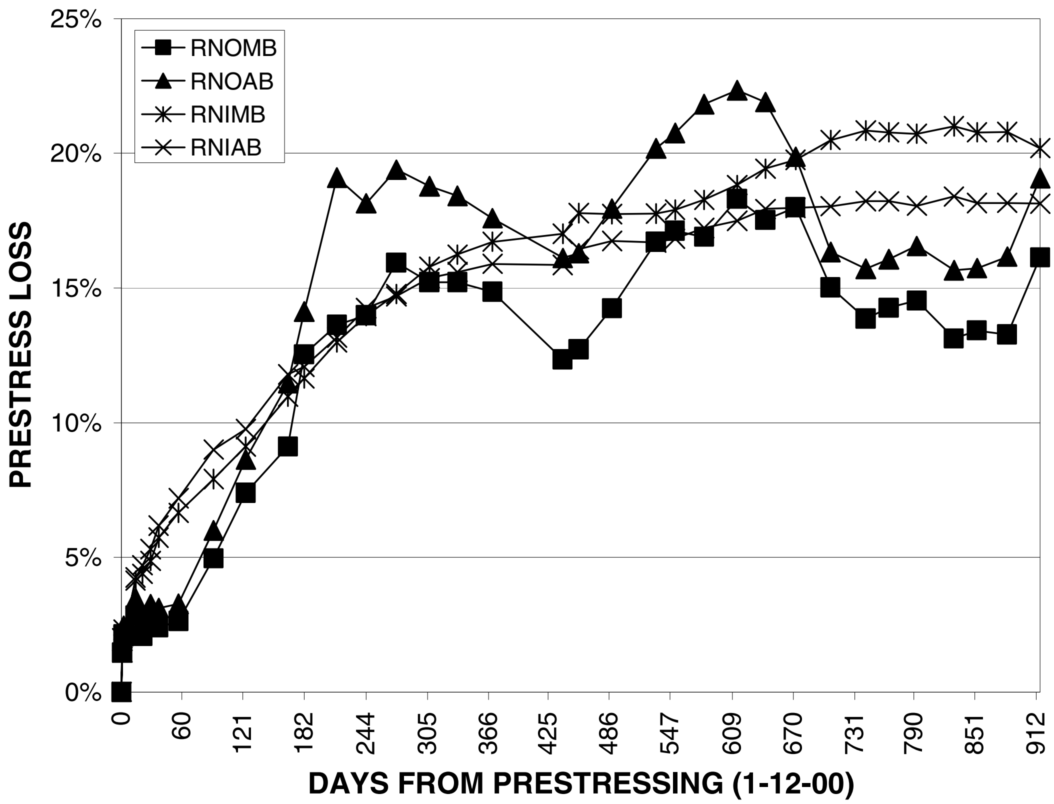

FIGURE 5 Box Girder Average Measured Loss as a Percentage of Initial Prestress

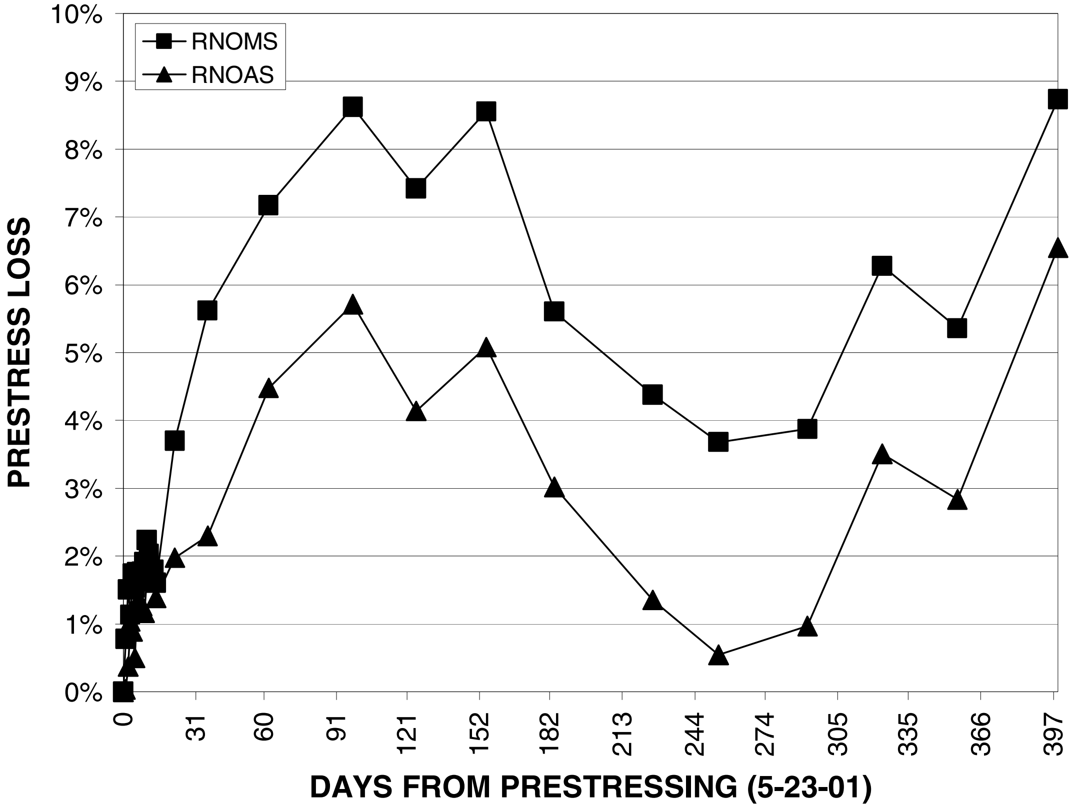

FIGURE 6 Solid Beam Mechanical Gage Loss as a Percentage of Initial Prestress

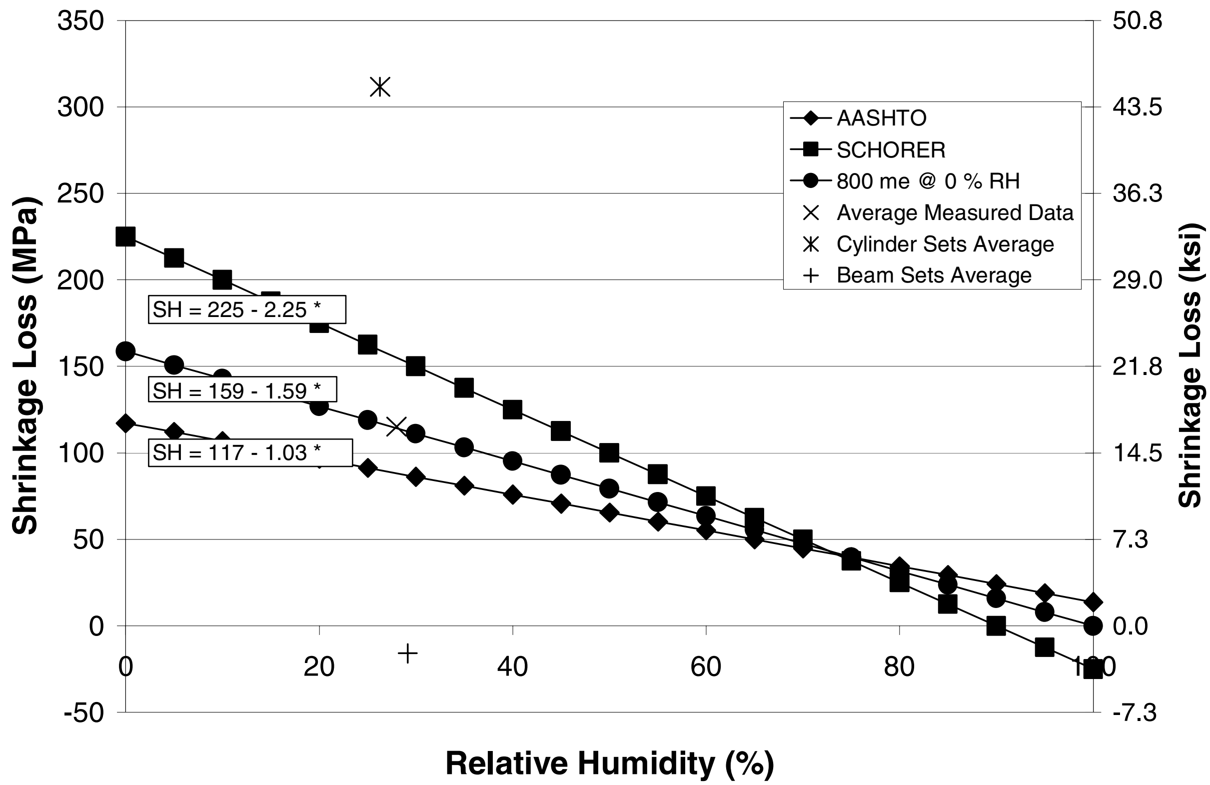

FIGURE 7 Shrinkage Equation Comparisons